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# Estimation of pasture drought severity using canopy red-to-far-red radiance

C. M. Feldhake<sup>a</sup>, D. M. Glenn<sup>b</sup>

<sup>a</sup>USDA, ARS, NAA, Appalachian Soil and Water Conservation Research Laboratory, PO Box 400, Beaver, WV 25813-0400, USA

<sup>b</sup>USDA, ARS, NAA, Appalachian Fruit Research Laboratory, Rte. 2, Box 45, Kearneysville, WV 25430, USA

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## Abstract

Reliable methods for quantifying the impact of drought on pasture leaf canopies in humid, temperate regions are not available. This study was conducted to determine the utility of the red-to-far-red ratio of canopy radiance for estimating the evapotranspiration (ET) rate of water-limited pasture during drought. The hypothesis that the relationship between the ET and the red-to-far-red ratio of radiance is not linear was evaluated. The ET and spectral radiance were measured for orchardgrass (*Dactylis glomerata* L.) and tall fescue (*Festuca arundinacea* Schreb.) growing in large monolith weighing lysimeters at Kearneysville, WV. Drought was imposed using rain-exclusion shelters during periods of predicted rainfall. During the study period, the ET decreased to 0.14 and 0.23 of the potential rates for orchardgrass and tall fescue respectively. The process by which the canopies of the two grass species senesced in response to severe drought differed. Despite this difference, a single non-linear relationship effectively estimated the ET for both grass species from the red-to-far-red ratio of canopy radiance under midday sunlight. This relationship may be a useful tool for developing improved pasture management strategies and for hydrologic assessment in regions dominated by pasture. © 1997 Elsevier Science B.V.

**Keywords:** Lysimeter; Tall fescue (*Festuca arundinacea* Schreb.); Orchardgrass (*Dactylis glomerata* L.); Water stress; Red-to-far-red ratio

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## 1. Introduction

The spectral characteristics of plants provide a unique signature compared with other terrestrial matter. Over a wavelength increase of less than 40 nm, leaves change from highly absorptive in the red to highly reflective in the far-red region [12]. Plants have evolved a system of photoreceptors called phytochromes, which are sensitive to the relative amounts of red and far-red radiation in their environment [20]. The ratio of red to far-red radi-

ation is used as a signal to indicate the amount of competing vegetation in a plant's immediate environment, and to trigger the appropriate physiological responses [2, 6].

Grasses exposed to radiation with a very low red-to-far-red ratio exhibit elongation of internodes, smaller and longer leaf blades, and reduced tillering [4, 5, 8, 11, 15]. Low red-to-far-red ratios typically occur when vegetation is shaded by other vegetation, so that the total light intensity is also low. Under these conditions, increased tiller death

[5] and advanced leaf senescence [13] are observed. Pastures in which biomass was not harvested began to decline in stand density in response to low red-to-far-red ratios at the plant crown [11].

Because of the unique spectral signature of vegetation in the red and far-red regions, the inverse ratio (near-IR-to-red ratio) is routinely used for remote sensing of vegetation type and density, particularly in arid and semi-arid areas [18, 19, 21]. This ratio is useful for estimating the leaf area index (LAI) for yield estimates, or for use in calculating potential evapotranspiration (ET) [3, 14].

Pasture vegetation dominates the landscape in many regions of the world, including much of the eastern and midwestern USA. Despite generally favorable regional precipitation, periodic drought is the greatest obstacle to optimal uniform forage production throughout the growing season [7]. With the adoption of intensive grazing systems, long-term pasture productivity is dependent on improved management systems. Improper management during drought can jeopardize the survival of desirable forage species and can allow 'weedy' invasions [22].

Pasture differs from field crop agriculture in that the plants are generally perennial. During severe drought, leaves senesce and new growth ceases until the arrival of precipitation. As leaves senesce, their spectral characteristics change dramatically. In the visible portion of the spectrum, reflectance increases several-fold as chlorophyll degrades [17]. In the far-red region of the spectrum, the reflectance decreases substantially as the integrity of the air–water–membrane interfaces decays.

These changes offer the potential for remote sensing of the drought severity and for estimating subsequent physiological responses to drought on renewed precipitation. Little information that direct links the severity of drought to the degree of canopy senescence is available. In areas with limited water, the percentage of vegetation cover, as determined using spectral indexes, is assumed to be linearly correlated with water use [9, 16, 23]. However, with complete canopy cover in a turfgrass study,

the relationship between the live biomass and the ET was not a simple linear relationship [10]. A better understanding of the relationship between canopy senescence and ET would not only increase our knowledge of how pasture ecosystems operate, but may also be of use in production management and regional hydrologic monitoring.

Our hypothesis is that the percentage of live biomass in a dense forage canopy is not linearly related to the ET during drought periods. We further hypothesize, however, that the red-to-far-red ratio of radiance, as a measure of the percentage of live biomass, is strongly correlated with the ET, so may have utility for quantifying drought.

## 2. Methods and materials

During the summer of 1992, ET was measured using two large (2.5 m × 2.5 m × 2.0 m) monolith weighing lysimeters (FS-8 scale, Cardinal Scale Manufacturing, Webb City, MO)\* at the Appalachian Fruit Research Station near Kearneysville, WV. Drought was imposed using 8.0 m × 9.0 m portable clear fiberglass rain-exclusion shelters during periods of predicted precipitation. The lysimeters were located 25 m apart in an open field of Hagerstown silt loam (fine, mixed mesic typic Hapludalf).

The spectral responses to drought of two grass species, i.e. tall fescue (*Festuca arundinacea* Schreb.) and orchardgrass (*Dactylis glomerata* L.), were assessed as being representative of the two major pasture grasses in Appalachia. Their canopies were comprised of lush regrowth from a late spring hay harvest and had attained a height of about 45 cm.

We measured the wet and dry bulb temperatures using aspirated copper–constantan thermocouples, and the wind velocity using a Met One 014A (Grants Pass, OR) wind speed sensor at a height of 1.3 m between the two lysimeters. The net radiation (REBS Q-6, Seattle, WA) was measured over each lysimeter and the canopy temperature from each was obtained using carborundum (Solon, OH) thermal IR sensors pointing at 0° and 180° from north at 60° from nadir.

Two soil heat flux plates (Thermonetics, San Diego, CA) were placed at a depth of 5 cm in each

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\*Mention of a particular product or company does not imply endorsement or preference over similar products not mentioned.

lysimeter, and the soil temperature was measured with two replications at 5 cm and four replications at the surface, using copper–constantan thermocouples.

Spectral scans were taken on cloud-free days. Three scans of radiance from 330 to 1100 nm over each lysimeter, and from a barium sulfate standard were carried out using an LI-1800 portable spectroradiometer (Lincoln, NE) with a fiberoptic probe attachment equipped with a telescopic lens. The measurements were taken 90° from the incident solar azimuth and 45° from nadir near noon. Each scan describes the radiance from a different surface region (area, 0.1 m<sup>2</sup>) of the lysimeter's vegetation under sunlight.

Scans of transmitted radiation under the canopy (at the soil surface) were also carried out in triplicate using the same instrumentation—except that the telescopic lens was replaced with a cosine-corrected dome. However, these measurements represent only a very small area of sampling (0.004 m<sup>2</sup>), although the sensor does measure radiation from the whole hemisphere.

The red-to-far-red ratio was calculated for radiance and transmitted radiation. For the red region, the energy was integrated between the wavelengths of 660 and 680 nm; for the far-red region, the wavelengths between 740 and 760 nm were used.

The amount of photosynthetically active radiation (PAR) transmitted through the canopy was measured periodically by inserting a Decagon PAR/Sunfleck Ceptometer (Pullman, WA) 1 m long into the base of the canopy at 12 sites within each lysimeter and averaging.

The potential ET (ET<sub>p</sub>) was calculated using the Penman combination equation for comparison with lysimetrically measured Et (ET<sub>a</sub>) [1]. Drought was quantified by calculating the relative ET (ET<sub>r</sub>) as

$$ET_r = ET_a / ET_p \quad (1)$$

### 3. Results and discussion

There were three periods of 8–9 days that were mostly sunny and where the lack of predicted precipitation allowed the continuous measurement of

the ET without being affected by the rain-exclusion shelters. The first period (DOY = 171–179) (days of year) was when the soil moisture was high and ET<sub>a</sub> was equal to ET<sub>p</sub>. During the second period (DOY = 215–221), ET<sub>r</sub> equalled 0.51 and 0.40 for the tall fescue and orchardgrass respectively; however, during the third period, ET<sub>r</sub> equalled 0.23 and 0.14 for the tall fescue and orchardgrass respectively.

Electronic malfunctioning as a result of lightning from thunderstorms interrupted continuous operation of the lysimeters outside of the three 8–9 day period. To estimate ET<sub>r</sub> during the days outside these periods when spectral scans were carried out, regression equations were used to predict ET<sub>r</sub> as a function of DOY, using data from the three periods of 8–9 days, along with an estimation of when water stress began to limit the ET by each grass species (DOY = 186 for tall fescue and DOY = 182 for orchardgrass). The regressions yielded

$$ET_r = \exp(-4.61 + 861/\text{DOY}), \quad r^2 = 0.99 \quad (2)$$

and

$$ET_r = \exp(-5.82 + 1064/\text{DOY}), \quad r^2 = 0.99 \quad (3)$$

for tall fescue and orchardgrass respectively.

The vertical canopy structure of each species did not change noticeably during the study period, despite the severe drought imposed. The light transmitted through each canopy did not change significantly (Table 1), although there did appear to

Table 1

Amount of PAR transmitted through orchardgrass and tall fescue canopies relative to incident quantity

DOY	Transmitted PAR (%)			
	Orchardgrass		Tall fescue	
	Mean <sup>a</sup>	Standard deviation	Mean <sup>a</sup>	Standard deviation
189	1.2 e	1.0	4.2 ab	3.0
219	1.8 cde	1.2	4.6 a	2.3
238	2.0 cde	0.9	3.7 abcd	1.7
259	2.1 bcde	1.2	3.7 abcd	1.5
275	1.7 de	1.1	4.1 abc	1.9

<sup>a</sup> Mean values followed by the same letter are not significantly different at the 0.05 level, using Tukey's multiple range test.

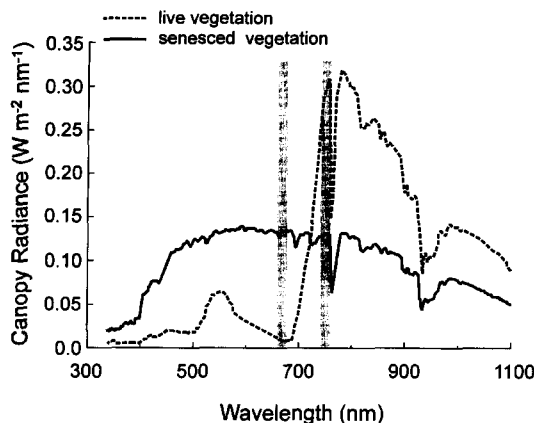


Fig. 1. Relative amount of canopy radiance between 330 and 1100 nm from orchardgrass that is lush green, and from orchardgrass that is totally senesced and brown as a result of herbicide application. The shaded bands indicate the red (660–680 nm) and far-red (740–760 nm) regions used to calculate the red-to-far-red ratio.

be a small overall difference between the tall fescue and orchardgrass. On average, the tall fescue allowed about 4% of the incident PAR through the canopy, while the orchardgrass allowed only 2%.

However, there are two striking changes in the spectral signature of vegetation as it senesces. One change is that the chlorophyll molecule degrades so that the visible wavelength radiance increases at all wavelengths (Figure 1). This imparts a visible brown color to vegetation. While the radiance at all visual wavelengths increases, the greatest relative increase is in the red region.

The other change that senescence causes is that water–cell wall–air space interface structures degrade [17]. In live plants, these cell interfaces are efficient at scattering and reflecting far-red radiation. As these interfaces degrade, plant leaves do not reflect far-red wavelengths as strongly, thus decreasing the radiance measured in that spectral region (Figure 1). The live biomass had a red-to-far-red ratio of about 0.1, while the totally senesced canopy had a ratio of about 1.1, i.e. more than an order of magnitude larger.

As the imposed drought progressed through the summer, the amount of senesced material in the plant canopies on the lysimeters increased. The red-to-far-red ratio of the canopy's radiance increased with time, in response to this vegetational change

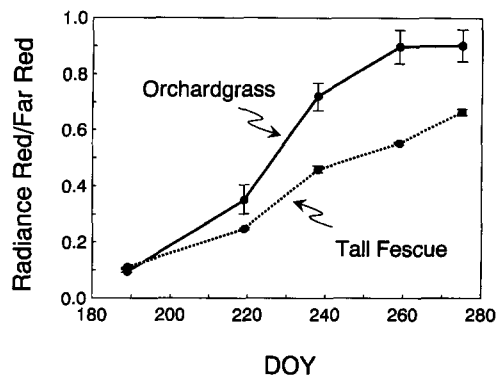


Fig. 2. Red-to-far-red ratio of radiance from the tall fescue and orchardgrass canopies throughout the drought-imposed period. Each point is the average of three measurements. The bar at each point represents the standard deviation.

(Figure 2). The ratio increased more rapidly for the orchardgrass than for the tall fescue.

The red-to-far-red ratio of the transmitted radiation also increased as drought progressed, in response to the canopy senescence (Figure 3). The values changed little after DOY = 238, but the small effective sampling surface area prevents a rigorous interpretation. The red-to-far-red ratio of the transmitted radiation was initially much greater than the radiance values, because more red penetrated into the canopy than was reflected, particularly for the tall fescue.

The increase in red-to-far-red ratio of transmitted radiation serves as a signal for grasses to increase tillering when water availability becomes sufficient,

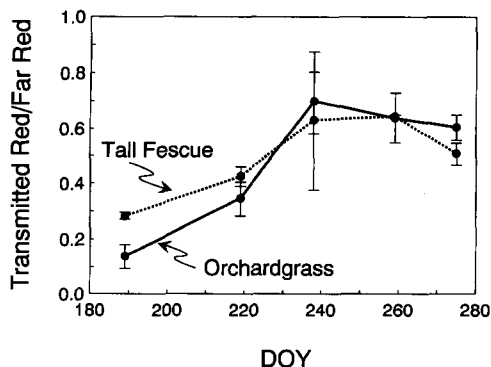


Fig. 3. Red-to-far-red ratio of solar radiation transmitted through the tall fescue and orchardgrass throughout the drought-imposed period. Each point is the average of three measurements. The bar at each point represents the standard deviation.

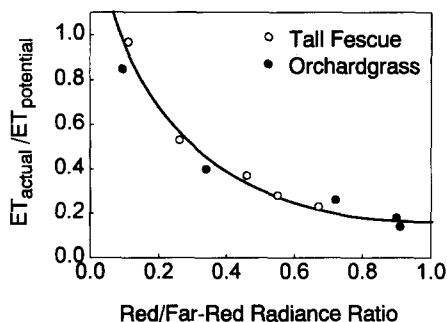


Fig. 4. Relative ET as a function of the canopy red-to-far-red ratio of radiance for combined tall fescue and orchardgrass data during the drought-imposed period. Each point is the average of three measurements of radiance, with small standard deviations at each point. (The radiance values are those from Fig. 2.)

to maximize capture of the increased light relative to competition from neighboring plants [4, 5, 8, 11, 15]. Also, as some leaves senesce, the resultant red-to-far-red ratio increase within the canopy may help retard further senescence [13].

The decrease in  $ET_r$  and the increase in the red-to-far-red ratio of radiance indicate that the orchardgrass was subjected to higher degrees of water stress than was the tall fescue at any given time after  $DOY=182$ . When  $ET_r$  was evaluated for its relationship to the red-to-far-red ratio of radiance for both species, however, the data coalesced into a single relationship (Figure 4), yielding the regression equation

$$y = 1/(-2.97 + 3.69 \exp x), \quad r^2 = 0.97 \quad (4)$$

where  $y$  is equal to  $ET_r$  and  $x$  is the red-to-far-red ratio.

The canopies of the two species differed considerably. The tall fescue's canopy was upright and more open to the vertical penetration of radiation. As the grass became water stressed, the leaf blades curled tightly, increasing the view of previously senesced material near the ground surface. Eventually, the live leaves began to senesce.

In contrast, the orchardgrass leaves were bent near the top and formed what could be considered effectively as a planar surface at the top of the canopy. This greatly restricted the field of view that the lower canopy regions had of the regions above. Under water stress, the leaves did not curl but

merely began to turn brown, beginning at the tip and progressing backwards.

Initial decreases in  $ET_r$  as a result of water stress resulted in only a small change in the red-to-far-red ratio, because grass canopies can tolerate some stress without substantial increases in leaf senescence. As  $ET_r$  decreased from 1.0 to 0.5, the red-to-far-red ratio of the canopy radiance only increased from 0.1 to 0.3. However, a subsequent decrease in  $ET_r$  to 0.2 raised the red-to-far-red ratio to 0.9 as the live biomass became a minor component of the canopy. These data demonstrate that the relationship between the red-to-far-red ratio of radiance and the  $ET_r$  is not linear for a dense forage canopy affected by drought.

Given the different mechanisms by which the two grasses respond to drought, one might question why the relationship between the red-to-far-red ratio and the  $ET_r$  would be the same. It may simply be fortuitous. However, both grasses occupy a similar ecological niche, and their spectral coupling to the environment during drought may represent an adaptive optimal condition.

It is not surprising that grasses should delay senescence when  $ET_r$  is reduced by drought. Should precipitation arrive before drought became severe, it would be advantageous to have a canopy of live biomass with which to renew maximum photosynthesis instead of regenerating new leaves.

#### 4. Conclusions

Despite different mechanisms by which tall fescue and orchardgrass became increasingly brown during drought periods, a single empirical relationship described  $ET_r$  as a function of the red-to-far-red ratio of radiance for both. Therefore, this ratio may be useful as a tool to assist decision-making in pasture management within humid, temperate areas, by providing a method for quantifying drought. It may also have utility for assisting with regional hydrological assessment in areas where a large percentage of the land is pasture. These data indicate that the assumption used in arid regions, i.e. that  $ET$  is linearly proportional to spectrally determined vegetation indexes, is not valid for humid climate pastures. The utilization of spectral

information of plants to infer rates of water utilization by large regions of pasture must include adjustments for plant resilience when exposed to drought; otherwise, large errors may result.

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